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Jackson et al.

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(54) **STACKED-DIE BULK ACOUSTIC WAVE OSCILLATOR PACKAGE**

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H03H 9/17	(2006.01)

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(52) **U.S. Cl.**

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(58) **Field of Classification Search**

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USPC .... 331/107 R
See application file for complete search history.

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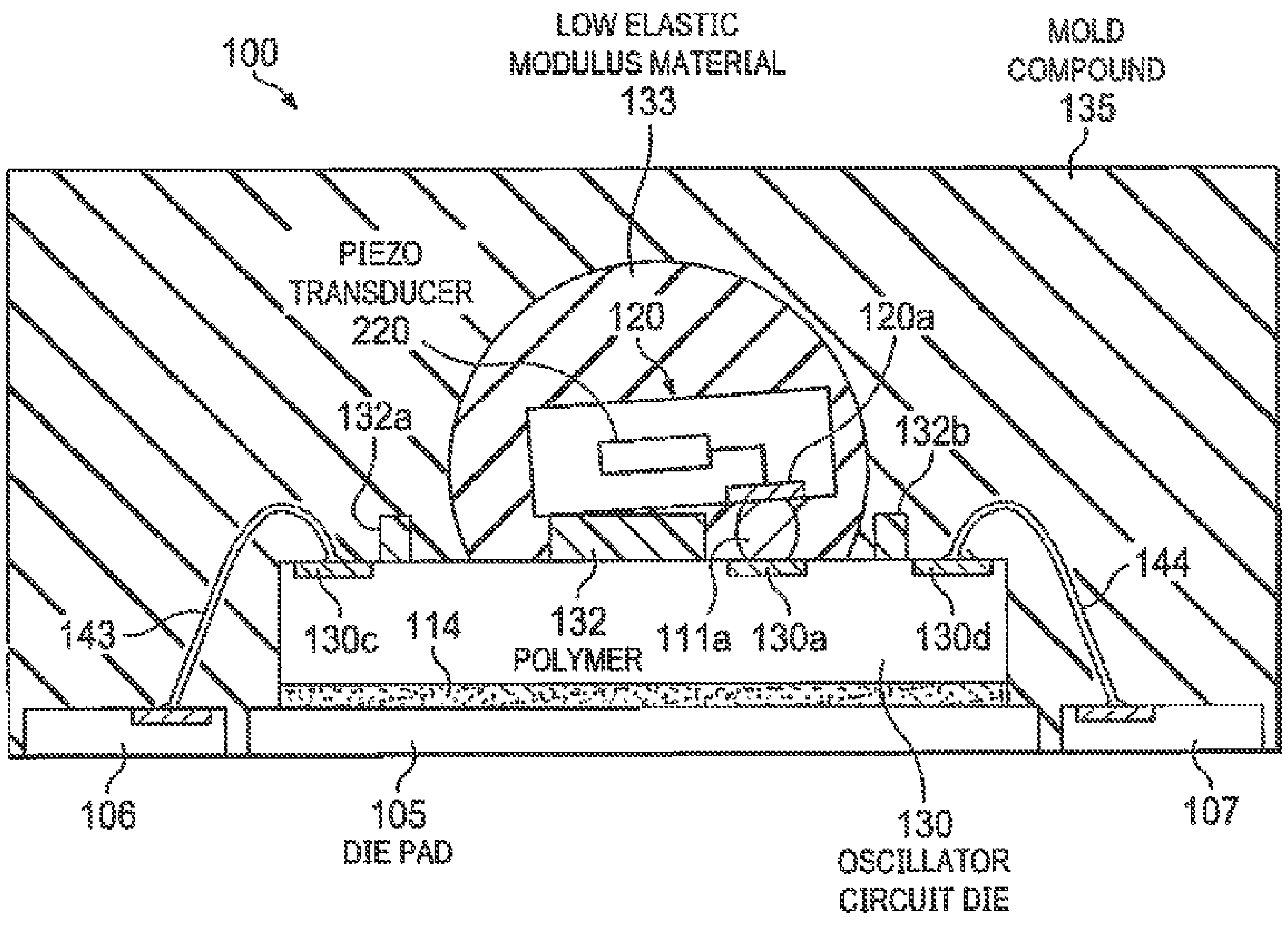
(74) *Attorney, Agent, or Firm* — Ronald O. Neerings; Charles A. Brill; Frank D. Cimino

(57) **ABSTRACT**

A stacked-die oscillator package includes an oscillator circuit die having inner bond pads, and outer bond pads, and a bulk acoustic wave (BAW) resonator die having a piezoelectric transducer with a first and second BAW bond pad on a same side coupled to a top and bottom electrode layer across a piezoelectric layer. A first metal bump is on the first BAW bond pad and a second metal bump is on the second BAW bond pad flip chip bonded to the inner bond pads of the oscillator circuit die. A polymer material is in a portion of a gap between the BAW and oscillator circuit die.

24 Claims, 4 Drawing Sheets



Related U.S. Application Data

continuation of application No. 15/968,435, filed on May 1, 2018, now Pat. No. 10,574,184.

(51) **Int. Cl.**

H01L 41/25	(2013.01)
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H01L 41/047	(2006.01)
H01L 23/495	(2006.01)
H01L 41/053	(2006.01)
H01L 23/31	(2006.01)
H01L 25/16	(2006.01)
H01L 21/78	(2006.01)
H01L 21/56	(2006.01)

(52) **U.S. Cl.**

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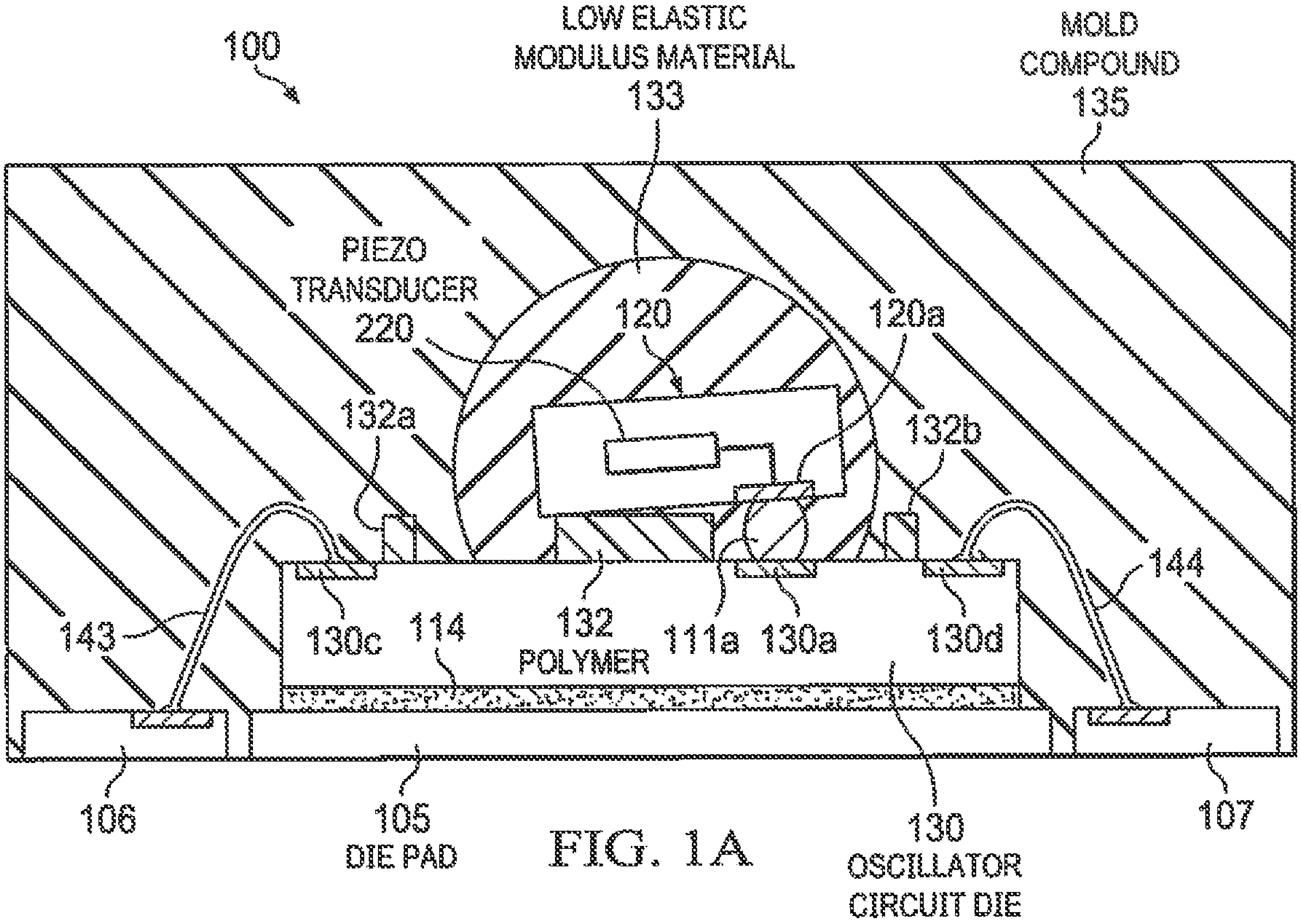


FIG. 1A

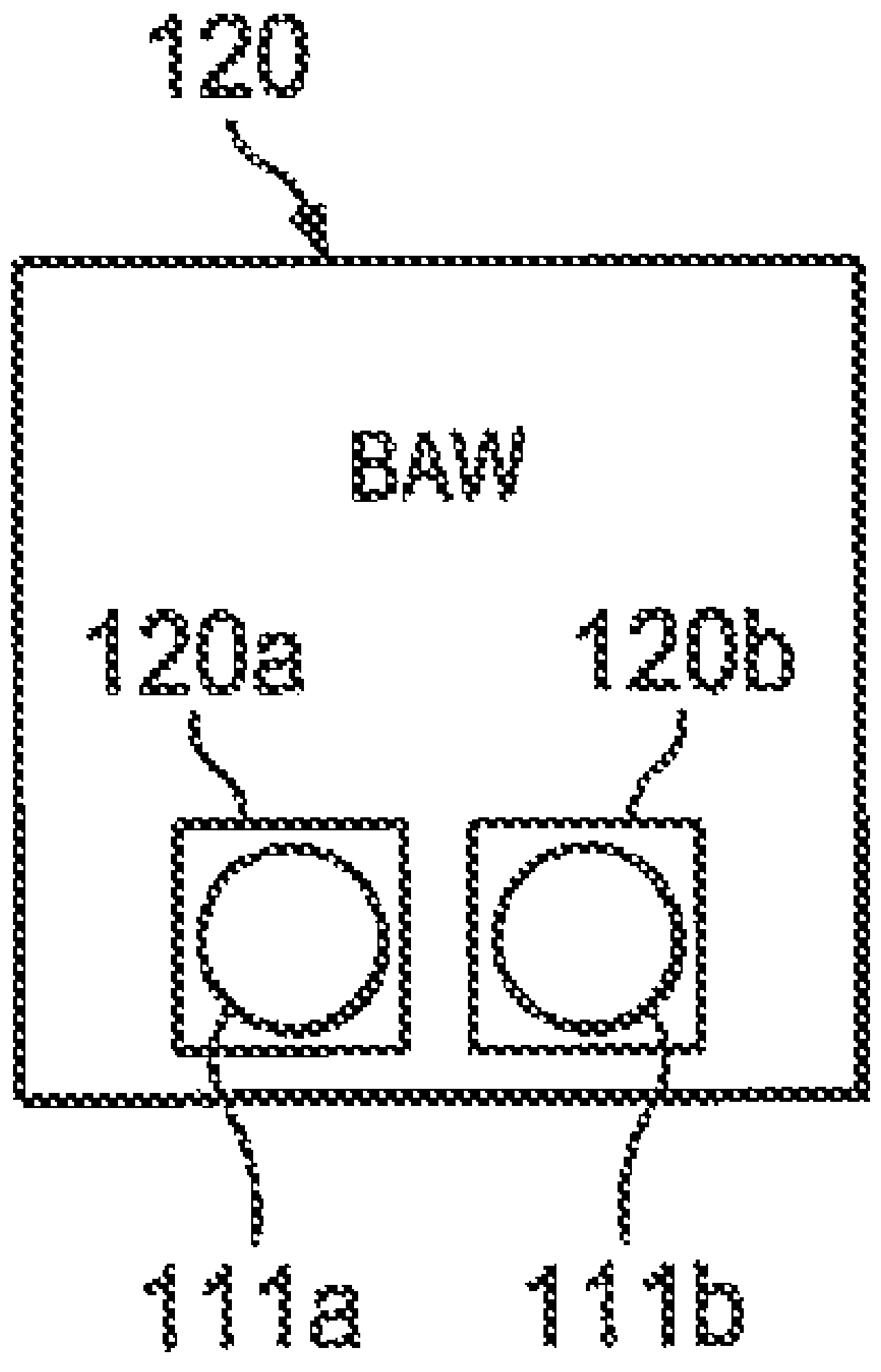


FIG. 1B

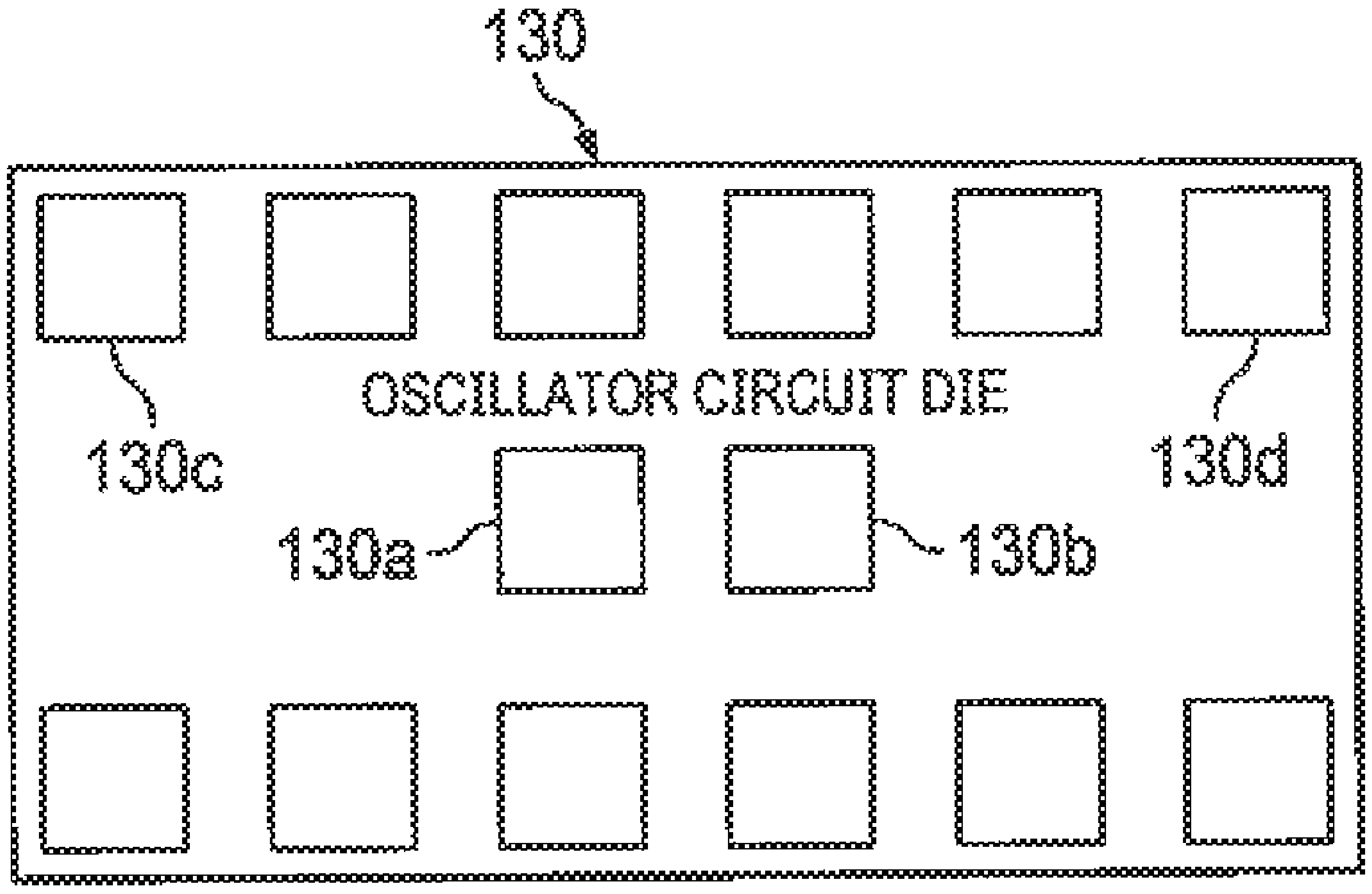


FIG. 1C

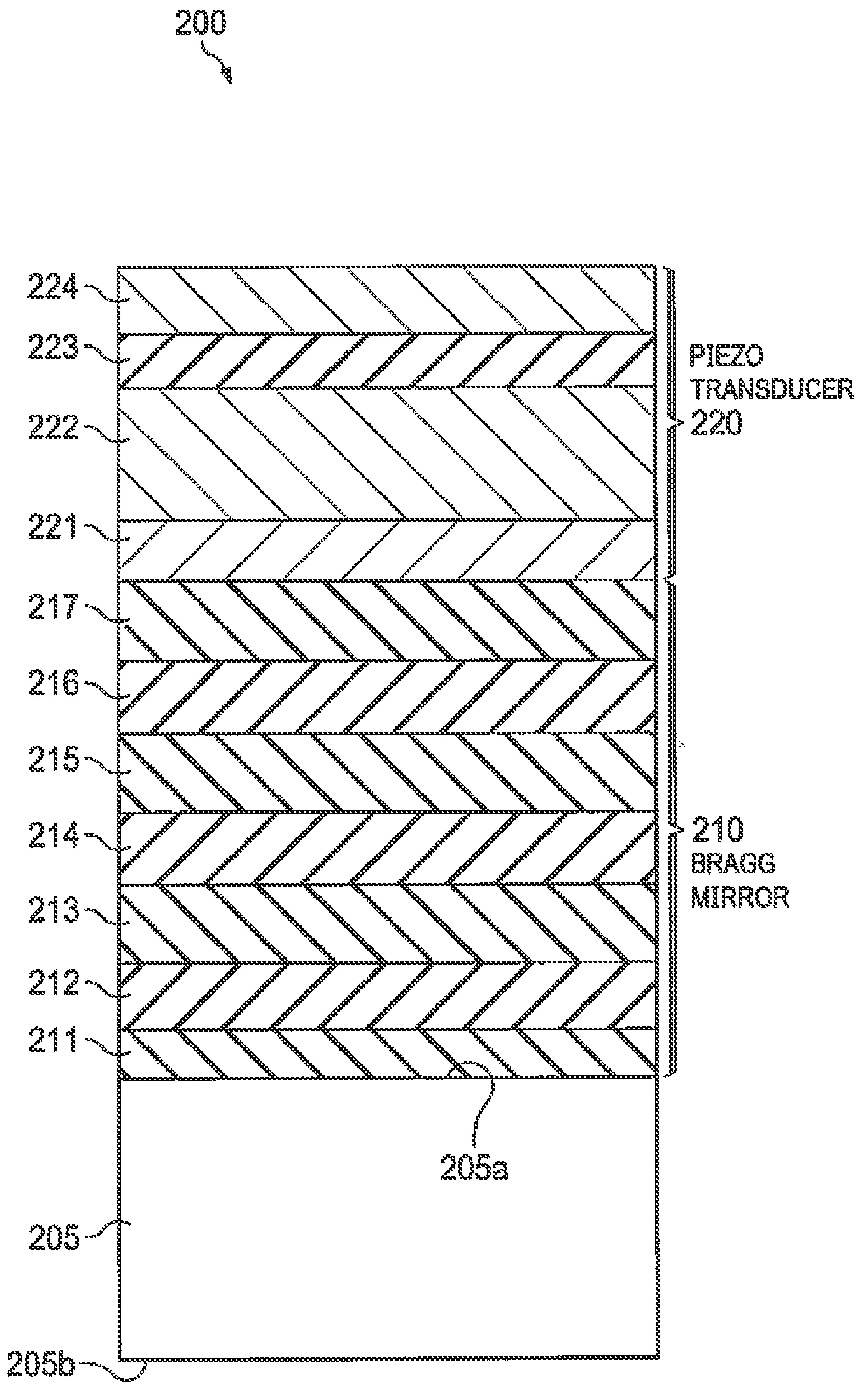
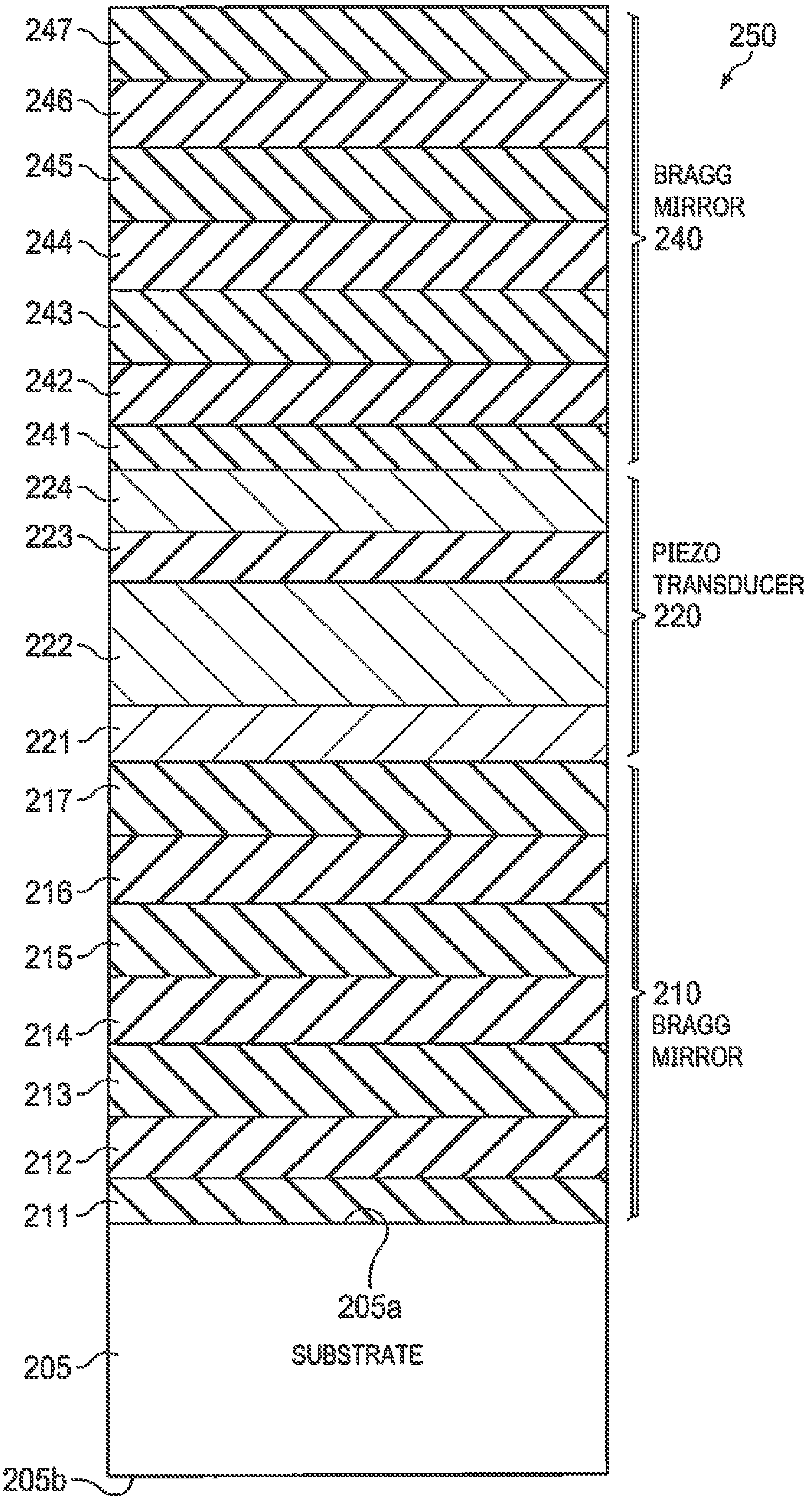

200
224
223
222
221
217
216
215
214
213
212
211
205a
205
205b
PIEZO
TRANSDUCER
220
210
BRAGG
MIRROR

FIG. 2A



250
247
246
245
244
243
242
241
BRAGG
MIRROR
240
224
223
PIEZO
TRANSDUCER
220
222
221
217
216
215
214
213
212
211
210
BRAGG
MIRROR
205a
SUBSTRATE
205
205b

FIG. 2B

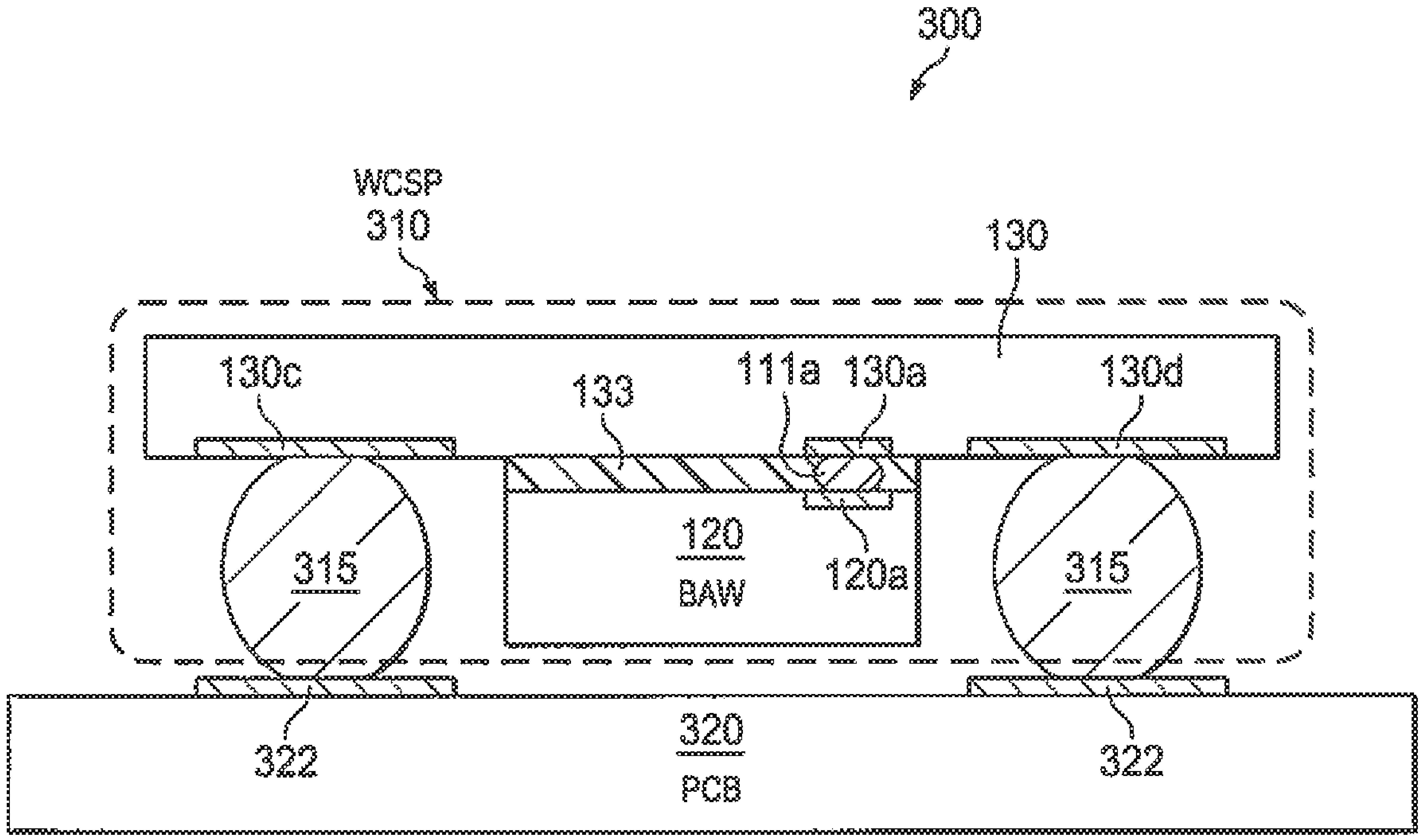

300
WCSP
310
130
130c
133
111a
130a
130d
315
120
BAW
120a
315
320
PCB
322
322

FIG. 3A

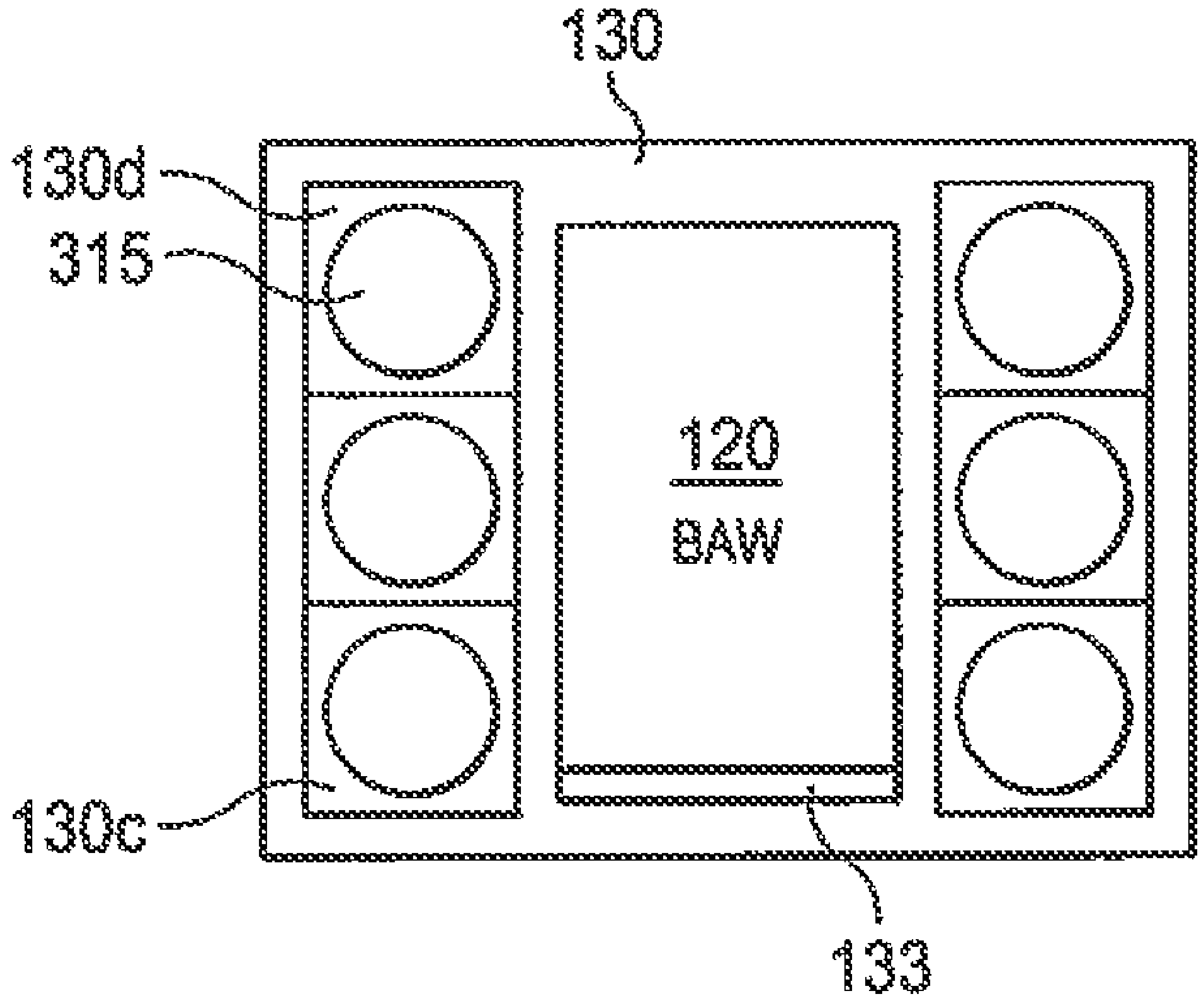

130
130d
315
120
BAW
130c
133

FIG. 3B

STACKED-DIE BULK ACOUSTIC WAVE OSCILLATOR PACKAGE

This application is a Continuation of application Ser. No. 16/747,679 filed Jan. 21, 2020, which is a Continuation of application Ser. No. 15/968,435 filed May 1, 2018, now U.S. Pat. No. 10,574,184.

FIELD

This Disclosure relates to packaged bulk acoustic wave oscillator devices.

BACKGROUND

Bulk acoustic wave (BAW) devices use the piezoelectric effect to convert electrical energy into mechanical energy resulting from an applied radio frequency (RF) voltage. BAW devices generally operate at their mechanical resonant frequency which is defined as that frequency for which the half wavelength of sound waves propagating in the device is equal to the total piezoelectric layer thickness for a given velocity of sound in the piezoelectric material. BAW resonators operating in the GHz range (e.g., at about 2 GHz) generally have physical dimensions of tens of microns in diameter with thicknesses of a few microns.

For functionality the piezoelectric layer of the BAW device is acoustically isolated from the substrate. There are two conventional device structures for acoustic isolation. The first is referred to as a Thin Film Bulk Acoustic Resonator (FBAR) device. In a FBAR device the acoustic isolation of the piezoelectric layer is achieved by removing the substrate or an appropriate sacrificial layer from beneath the electroded piezoelectric resonating component to provide an air gap cavity.

The second known device structure for providing acoustic isolation is referred to as a Solidly Mounted Resonator (SMR) device. In a SMR device the acoustic isolation is achieved by having the piezoelectric resonator on top of a highly efficient acoustic Bragg reflector that is on the substrate. The acoustic Bragg reflector includes a plurality of layers with alternating high and low acoustic impedance layers. The thickness of each of these layers is fixed to be one quarter wavelength of the resonant frequency. A variant of the SMR device adds a second Bragg mirror on the top of the piezoelectric resonator of BAW resonator. A conventional BAW oscillator leadframe package comprises a BAW die side-by-side with an oscillator circuit die that have bond pads which are coupled die-to-die by bond wires. Gold (Au) bond wires can be used for this die-to-die coupling.

SUMMARY

This Summary is provided to introduce a brief selection of disclosed concepts in a simplified form that are further described below in the Detailed Description including the drawings provided. This Summary is not intended to limit the claimed subject matter's scope.

Disclosed aspects recognize for a conventional BAW oscillator package with a BAW resonator die and oscillator circuit die side-by-side that are coupled together by bond wires, the bond wires generally add significant parasitic capacitance, and moreover a variation in this capacitance can degrade the performance of the BAW oscillator package. Reducing this parasitic capacitance by eliminating the bond wires while providing good stress isolation for the BAW resonator die can improve the overall BAW oscillator package performance by improving the performance of the BAW resonator die. Assembly manufacturing tolerances are also generally improved by eliminating bond wires for disclosed BAW die-to-oscillator circuit die coupling.

This Disclosure includes a stacked-die BAW oscillator package with bump coupling between a top BAW resonator die that is flip chip attached to a larger area bottom oscillator circuit die which replaces the conventional bond wires coupling the BAW resonator die to the oscillator circuit die. Disclosed aspects include a stacked-die oscillator package including an oscillator circuit die having inner bond pads and outer bond pads, and a BAW resonator die having a piezoelectric transducer thereon having a first and a second BAW bond pad on a same side of the BAW resonator die coupled to a top and bottom electrode layer, that are across a piezoelectric layer. A first metal bump is on the first BAW bond pad, and a second metal bump is on the second BAW bond pad, which are flip chip bonded to the inner bond pads of the oscillator circuit die.

BRIEF DESCRIPTION OF THE DRAWINGS

Reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, wherein:

FIG. **1**A is a cross sectional view of an example stacked-die BAW oscillator leadframe package with bumps showing bump coupling between bond pads on the BAW die and inner bond pads on the oscillator circuit die.

FIG. **1**B shows the bumps on the same side of the BAW resonator die.

FIG. **1**C shows the inner and outer bond pads on the oscillator circuit die.

FIG. **2**A is a cross sectional depiction that shows a layer stack for a BAW resonator die comprising a SMR device.

FIG. **2**B is a cross sectional depiction that shows a layer stack of a BAW resonator die comprising a dual-Bragg mirror.

FIG. **3**A is a cross sectional view of a printed circuit board (PCB) assembly comprising an example stacked-die BAW oscillator as a Wafer Chip Scale Package (WCSP) with bump coupling between bond pads on the BAW die and inner bond pads on the oscillator circuit die, where the WCSP is assembled onto land pads on the surface a PCB.

FIG. **3**B is a view from underneath the WCSP shown in FIG. **3**A.

DETAILED DESCRIPTION

Example embodiments are described with reference to the drawings, wherein like reference numerals are used to designate similar or equivalent elements. Illustrated ordering of acts or events should not be considered as limiting, as some acts or events may occur in different order and/or concurrently with other acts or events. Furthermore, some illustrated acts or events may not be required to implement a methodology in accordance with this Disclosure.

FIG. **1**A is a cross sectional view of an example stacked-die BAW oscillator leadframe package **100** that includes an oscillator circuit die **130** on a leadframe and a BAW resonator die **120** flip chip bonded to the oscillator circuit die **130**, shown with a BAW bond pad **120***a* bonded by bump **111***a* to an inner bond pad **130***a* of the oscillator circuit die **130**. As compared to a conventional wire bonded die-to-die arrangement, the flip chip connection utilized by the stacked-die oscillator leadframe package **100** provides shorter electrical routing between the BAW resonator die **120** and oscillator circuit die **130** which reduces the parasitic capacitance. Disclosed bump connections eliminate the generally difficult conventional die-to-die wire bonding process while providing low capacitance interconnections that are more consistent from stacked-die oscillator package to package.

The leadframe includes a die pad **105** and a plurality of lead fingers shown as **106**, **107**. FIG. **1**B shows the bumps **111***a*, **111***b* on BAW bond pads **120***a*, **120***b* that are both on the same side of the BAW resonator die **120**, while FIG. **1**C shows the inner bond pads **130***a*, **130***b* and outer bond pads **130***c*, **130***d*, as well other outer bond pads (un-numbered) on the oscillator circuit die **130**.

Besides the first metal bump **111***a* shown in FIG. **1**A on the first BAW bond pad **120***a* there is the second metal bump **111***b* shown in FIG. **1**B on the second BAW bond pad **120***b*, that are both flip chip bonded to the inner bond pads **130***a*, **130***b* of the oscillator circuit die **130**. Disclosed stacked-die oscillator package **100** maintains good stress isolation by having the BAW bond pads **120***a*, **120***b* and thus all the bumps **111***a*, **111***b* on one side of the BAW resonator die **120** to form a diving board type (linear or cantilever-like) bump configuration.

The bumps **111***a* and **111***b* can comprise a copper (Cu) post with a different metal cap thereon. A typical solder bump material is a Cu post with a Ni—Pd cap or a AgSn solder material cap. The bumps **111***a* and **111***b* can also comprises Au bumps. The outer edges of the bumps **111***a* and **111***b* are generally spaced apart by a minimum gap of 30 μm to provide a sufficient minimum clearance to help prevent shorts between the bumps.

The BAW resonator die **120** has a piezoelectric transducer **220** with a first and second BAW bond pad **120***a*, **120***b* on a same side of the die coupled to a top and bottom electrode layer across a piezoelectric layer. FIG. **2**A described in more detail below shows a piezoelectric transducer **220** including a top electrode layer **224** and bottom electrode layer **221** across a piezoelectric layer **222**. Having all the BAW die connections to the oscillator circuit die **130** on one side of the BAW resonator die **120** forms a pivot point with a pivot on the bumps **111***a* and **111***b*.

A low elastic modulus material **133** that generally comprises a polymer is shown in FIG. **1**A that helps prevent package stress transferring into the BAW resonator die **120**. Being on one side a cantilever-like structure formed, with only two semi-flexible points of attachment being the bumps, surrounded with a low elastic modulus material **133** such as silicone or an epoxy, helps protect the BAW die **120** from external stresses. For example, stress from the mold compound **135** itself or from an external force can transfer stress to the BAW die **120** which can degrade its performance. Having the bump connections all on one side also helps to prevent coupling stresses from the oscillator circuit die **130** into the BAW die **120**. Although not shown, the BAW die **120** can have more than 2 bond pads each with bumps thereon, such as to add a ground connection to the substrate of the BAW die **120**, or to add bond pads and bumps for implementing an on-chip temperature sensor.

If the oscillator circuit die **130** on the bottom of the BAW oscillator package **100** bends for instance, this stress can end up moving the BAW resonator die **120** slightly in the low elastic modulus material **133** versus conventional bending the BAW die and thus inducing stress on the films within the BAW resonator die **120**. The outer bond pads **130***c*, **130***d* are shown wire bound by bond wire **143** and **144** to lead fingers **106** and **107** of the leadframe, respectively. The oscillator circuit die **130** is attached to the die pad **105** by a die attach material **114**, such as a conventional epoxy.

A polymer material **132** or a low elastic modulus material **133** that as described above is generally also a polymer is in a portion of a gap between the BAW resonator die **120** and oscillator circuit die **130** that functions as a stand-off on the side of the BAW die **120** opposite the bumps. Such a stand-off structure helps with planarity during BAW resonator die **120** flip chip attach. The polymer material **132** or a low elastic modulus material **133** when functioning as a standoff as opposed to a single feature can optionally be in the form of a plurality of stripes. The polymer material **132** or a low elastic modulus material **133** can be formed on the BAW die, formed on the oscillator circuit die **130**, or be formed on both of these die, generally to a thickness of about 10 μm. The bump is generally about 25 micron high and 30 μm in diameter, so that the bumps are generally taller as compared to a thickness of the polymer material **132**, which is shown in FIG. **1**A.

The polymer material **132** can comprise a polyimide. The polymer material **132** is also shown in other regions in FIG. **1**A shown as regions **132***a* and **132***b* forming a surrounding dam for controlling possible bleed-out during the dispensing of a glob of the low elastic modulus material **133** described below which can help with die planarity during bumping. Polymers for the polymer material **132** can comprise polymers other than PI such as SU8 which comprises an epoxy-based material (conventionally used as a negative photoresist) comprising a Bisphenol A Novolac epoxy that is dissolved in an organic solvent (gamma-butyrolactone (GBL) or cyclopentanone, depending on the formulation) with up to 10 wt. % of mixed Triarylsulfonium/hexafluoroantimonate salt as the photoacid generator.

A mold compound **135** encapsulates the stacked-die oscillator package **100**, and a low elastic modulus material **133** (which can be the same material describe above that is in a portion of a gap between the BAW resonator die **120** and oscillator circuit die **130** that functions as a stand-off) is over the BAW resonator die **120** for encapsulating the BAW resonator die **120**, which can also filling any gaps under the BAW resonator die **120**. The low elastic modulus material **133**, such as silicone rubber, over the BAW die **120** helps isolate stress from the BAW resonator die **120**. For example, stress from the mold compound **135** or external forces can transfer stress to the BAW resonator die **120**. As described above, having the all bump connections on one side of the BAW resonator die **120** helps to prevent coupling stresses from the oscillator circuit die **130** with the oscillator into the BAW resonator die **120**. If the oscillator circuit die **130** bends for instance, the stress would end up moving the BAW resonator die **120** slightly in the low elastic modulus material **133** versus bending the BAW resonator die **120** that induces stress on the films within the BAW resonator die **120**.

As known in physics, an elastic modulus (or Young's Modulus) is defined as the ratio of longitudinal stress to longitudinal strain. Rubber-like behavior corresponds to a low elastic modulus value of about 10^6 N/m^2 (1 MPa) to 10^7 N/m^2 (10 MPa). A low elastic modulus material **133** as defined herein is a material that has a 25° C. elastic modulus of <50 MPa. Silicone rubber has siloxane bonds (—Si—O—Si), and has a Young's modulus at 25° C. of about 10 to 20 MPa. The low elastic modulus material **133** can be selected to have an elastic modulus of <10 MPa, such as 2 MPa to 10 MPa.

FIG. **2**A is a cross sectional depiction that shows a layer stack for a BAW resonator **200** comprising a SMR device. BAW resonator **200** includes a substrate **205** (e.g., silicon) having a top side surface **205***a* and a bottom side surface

205*b*. A Bragg mirror **210** is on the top side surface **205***a* of the substrate. Bragg mirror **210** comprises a plurality of layers with alternating high and low acoustic impedance layers, with the relatively high acoustic impedance layers shown as **212**, **214** and **216**, alternating with the relatively low acoustic impedance layers **211**, **213**, **215** and **217**. The thickness of each of these layers **211**-**217** is fixed to be about one quarter wavelength of the desired resonant frequency.

The piezoelectric transducer **220** shown includes a bottom electrode layer **221** that is on layer **217** of the Bragg mirror **210**, a piezoelectric layer **222** on the bottom electrode layer **221**, a dielectric layer **223** on the piezoelectric layer **222**, and a top electrode layer **224** on the dielectric layer. The dielectric layer **223** above the piezoelectric transducer **220** helps to reduce the temperature coefficient of frequency for BAW resonator **200**. Although not shown, BAW resonator **200** is generally in a hermetically sealed cavity to protect its top surface.

FIG. **2**B is a cross sectional depiction that shows a layer stack of a BAW resonator die **250** comprising a dual-Bragg mirror including both a bottom Bragg mirror **210**, and also top Bragg mirror **240**. The top Bragg mirror **240** being on top of the BAW resonator **200** shown in FIG. **2**A results in a BAW resonator **250** becoming essentially resistant to frequency shifts caused by the deposition on contaminants on top of the piezoelectric transducer **220**. Analogous to bottom Bragg mirror **210**, the top Bragg mirror **240** comprises a plurality of layers with alternating high and low acoustic impedance layers, with the relatively high acoustic impedance layers shown as **242**, **244** and **246**, alternating with the relatively low acoustic impedance layers **241**, **243**, **245** and **247**. The thickness of each of these layers **241**-**247** is fixed to be about one quarter wavelength of the desired resonant frequency.

As described above bumps (bumps **111***a*, **111***b* in FIG. **1**B) connect the bond pads on the BAW resonator die **120** to inner bond pads **130***a*, **130***b* on the oscillator circuit die **130**. The signals that are sent through from the oscillator circuit die **130** travel through metal interconnect on the oscillator circuit die **130** through the inner bond pads **130***a*, **130***b* on the oscillator circuit die **130** through the bumps, then through the bond pads on the BAW resonator die **120** and to its resonator through the electrode metal (in layer **221**, **224** in FIG. **2**A) on the BAW resonator die **120**.

FIG. **3**A is a cross sectional view of a PCB assembly **300** comprising an example stacked-die BAW oscillator Wafer Chip Scale Package (WCSP) **310** assembled onto a PCB. The WSCP **310** has bump coupling with a bump **111***a* shown between a bond pad **120***a* on the BAW die **120** and an inner bond pad **130***a* on the oscillator circuit die **130**. The stacked die **120**/**130** is assembled by bumps **315** (typically solder balls) that couple the outer bond pads **130***c*, **130***d* of the oscillator die **130** onto land pads **322** (e.g., Solder Mask Defined (SMD) pads) on the surface of a printed circuit board (PCB) **320**. No bond wires or interposer connections are needed by WCSP **310**. A low elastic modulus material **133** is shown in a gap between the BAW resonator die **120** and the oscillator circuit die **130** on the side opposite the bumps shown as bump **111***a*. Although shown flush to the BAW die **120** edges, the low elastic modulus material **133** will generally extend beyond the edges of the BAW die **120**, but can also be recessed relative to these edges.

FIG. **3**B is a view from underneath the example stacked-die BAW oscillator WCSP **310** shown in FIG. **3**A. In one specific example, the oscillator circuit die **130** is 1250 μm by 1500 μm in area, and the BAW die **120** is 550 μm by 878 μm in area, and has a thickness of 150 μm.

Disclosed stacked-die oscillator packages with bump coupling between the BAW resonator die **120** and oscillator circuit die **130** solve the problem for BAW technology needing good stress isolation and lower parasitic capacitance to provide improved stacked-die oscillator package performance. The disclosed bump die attach connections shorten the connection length between the BAW die **120** and the oscillator circuit die **130**, and also reduce the parasitic resistance, as well as the parasitic resistance.

Performance parameters for stacked-die oscillator packages include a series resistance resonance frequency (Fs), an anti-resonance or parallel resistance resonance frequency (Fp), and K_2eff % value which is defined by the difference between Fs and Fp. The performance improvement provided by disclosed stacked-die oscillator packages comprises a reduced frequency shift due to less parasitic capacitance resulting from disclosed bump connections between the BAW die **120** and the oscillator circuit die **130** as compared to conventional wire bond connections for known side-by-side oscillator packages that are known to shift the frequency. A higher relative K_2eff % value is also provided by reduced parasitic capacitance that is known to pull the Fs in closer to Fp. There is also less capacitive loading which results in a wider frequency oscillation window because of the reduced parasitic capacitance. Other advantages of disclosed stacked-die oscillator packages include a lower resistive path for connection of BAW die **120** to oscillator circuit die **130**. Shortened connections should also provide a lower risk for capacitive coupling of external noise which can couple in high frequency signals.

Those skilled in the art to which this Disclosure relates will appreciate that many other embodiments and variations of embodiments are possible within the scope of the claimed invention, and further additions, deletions, substitutions and modifications may be made to the described embodiments without departing from the scope of this Disclosure.

The invention claimed is:

1. A stacked-die oscillator package, comprising:

an oscillator circuit die having a first and a second bond pad;

a bulk acoustic wave (BAW) resonator die flip chip bonded to the first and second bond pads of the oscillator circuit die; and

a polymer material positioned in a portion of a gap between the BAW resonator die and the oscillator circuit die.

2. The stacked-die oscillator package of claim **1**, wherein the bulk acoustic wave (BAW) resonator die comprises a piezoelectric transducer.

3. The stacked-die oscillator package of claim **2**, further comprising a Bragg mirror above the piezoelectric transducer.

4. The stacked-die oscillator package of claim **1**, wherein the first metal bump and the second metal bump comprise a copper post with a different metal cap thereon.

5. The stacked-die oscillator package of claim **1**, wherein the polymer material comprises a polyimide.

6. The stacked-die oscillator package of claim **1**, further comprising a low elastic modulus material positioned over the BAW resonator die for encapsulating the BAW resonator die.

7. The stacked-die oscillator package of claim **6**, wherein the low elastic modulus material comprises silicone rubber.

8. The stacked-die oscillator package of claim **1**, wherein the polymer material comprises a low elastic modulus material.

9. The stacked-die oscillator package of claim **8**, wherein the polymer material also provides other polymer material regions including providing a surrounding dam for controlling bleed-out during a dispensing of a glob of the low elastic modulus material.

10. The stacked-die oscillator package of claim **1**, wherein the stacked-die oscillator package comprises a wire bound package further comprising a leadframe including a die pad and a plurality of lead fingers, wherein the oscillator circuit die is on the die pad, and bond wires coupling additional bond pads on the oscillator circuit die to the plurality of lead fingers, and a mold compound encapsulating the stacked-die oscillator package.

11. The stacked-die oscillator package of claim **1**, wherein the stacked-die oscillator package comprises a Wafer Chip Scale Package (WCSP).

12. A method of assembling a stacked-die oscillator package, comprising:

providing (i) an oscillator circuit die having bond pads comprising a first and a second bond pad, and (ii) a bulk acoustic wave (BAW) resonator;

forming a polymer material on a surface of the oscillator circuit die or on a surface of the BAW resonator die in at least a first polymer material region;

flip chip bonding the BAW resonator die to the oscillator circuit die so that the first polymer material region is between the BAW resonator die and the oscillator circuit die.

13. The method of claim **12**, wherein the providing the BAW resonator die comprises providing a Bragg mirror above the piezoelectric transducer.

14. The method of claim **12**, wherein the stacked-die oscillator package further comprises a leadframe including a die pad and a plurality of lead fingers, wherein the oscillator circuit die is on the die pad, further comprising:

wire bonding bond wires between other bond pads of the oscillator circuit die and the plurality of lead fingers, and

forming a mold compound encapsulating the stacked-die oscillator package.

15. The method of claim **14**, further comprising before the wire bonding encapsulating the BAW die by dispensing a glob of low elastic modulus material for encapsulating the BAW resonator die.

16. The method of claim **15**, wherein the forming the polymer material also provides other polymer material regions including a forming a surrounding dam for controlling bleed-out during the dispensing of the glob of low elastic modulus material.

17. The method of claim **12**, a bulk acoustic wave (BAW) resonator die comprising a first bond pad on the BAW and a second bond pad on the BAW, a first metal bump on the first BAW bond pad and a second metal bump on the second BAW bond pad wherein the first metal bump and the second metal bump comprise a copper post with a different metal cap thereon.

18. The method of claim **17**, wherein the polymer material comprises a polyimide.

19. The method of claim **15**, wherein the glob of low elastic modulus material comprises silicone rubber.

20. The method of claim **12**, wherein the polymer material comprises a low elastic modulus material, further comprising forming bumps on the other bond pads to provide a Wafer Chip Scale Package (WCSP), and then assembling the bumps on the other bond pads to land pads on a printed circuit board (PCB).

21. The stacked-die oscillator package of claim **13**, further comprising a Bragg mirror below the piezoelectric transducer.

22. The stacked-die oscillator package of claim **13**, further comprising a first Bragg mirror below the piezoelectric transducer and a second Bragg mirror above the piezoelectric transducer.

23. The stacked-die oscillator package of claim **12**, further comprising a printed circuit board (PCB), a first bump coupling a first land pad on the PCB to one of other bond pads on the oscillator circuit die and a second bump coupling a second land pad on the PCB to another of the other bond pads.

24. The stacked-die oscillator package of claim **12**, further including a printed circuit board (PCB), a first bump bonding one of other bond pads of the oscillator circuit die to a first land pad on the PCB and a second bump bonding another of the other bond pads of the oscillator circuit die to a second land pad on the PCB.

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